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MEROMORPHIC CONTINUATION OF POWER SERIES

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Abstract. In this paper, we offer a proposition enabling make an assessment of meromorphic continuation of power series by means of a specially defined polynomial $q_{n,m}(\alpha)$ using the coefficients of the Taylor series.

Key words: Meromorphic continuation, radius m-meromorphy, inverse theorem of Padé approximation
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Questions about meromorhic continuation of power series have interested the mathematicians for a rather long time. Already in 1892 Hadamar obtained some important results in this direction (see [4]) last 30 years these problems were again in consideration by the mathematicians due to some results obtained through Padé approximants (see [2, 3, 5]). Here we suggest a statement which gives the opportunity to estimate the meromorhic continuation of power series.

Let

$$\sum_{n=0}^{+\infty} f_n z^n \tag{1}$$

be an arbitrary power series and $R_0 = R_0(f)$ be the radius of convergence. If $R_0 > 0$ by $f = f(z)$ we will denote the sum of the series (1) in the disk of convergence $D_0 = \{z : |z| < R_0\}$ and the analytic function defined by the element (f, D_0) as well. In that case for each $m \in N$ we denote $D_m = D_m(f)$ to be the disk of m-meromorphy of f (the maximum open disk with a center O

in which $f(z), z \in D_0$ could be continued as a meromorphic function, having no more that m poles, taking into account their multiplicities), and let $R_m = R_m(f)$ be the radius of D_m . As usual C will be the complex plain.

Let $\Delta_{n,m}(f)$ be the determinant

$$(2) \qquad \triangle_{n,m}(f) = \begin{vmatrix} f_{n-m+1} & f_{n-m+2} & \cdots & f_n \\ f_{n-m+1} & f_{n-m+2} & \cdots & f_n \\ \cdots & \cdots & \cdots & \cdots \\ f_{n-m+1} & f_{n-m+2} & \cdots & f_n \end{vmatrix}, \quad \triangle_{n,0}(f) = 1,$$

$(f_{-k} = 0,\ k \in N)$.

On the assumption that $\Delta_n, m(f) \neq 0$ $(n \geq n_0, m \in N)$ we put

$$(3) \qquad q_{n,m}(\alpha) = q_{n,m}(\alpha, f) = (-1)^m \frac{\Delta_{n,m}((z-\alpha)f)}{\Delta_{n,m}(f)}$$

Let us mark that $q_{n,m}(\alpha)$ is polynomial of m degree with a coefficient in front of the highest degree 1, whose zeros we we shall denote with $\alpha_{n,j}$, $j = 1, 2, 3, ..., m,$ i.e.

$$(4) \qquad q_{n,m}(\alpha) = \prod_{j=1}^{m} (\alpha - \alpha_{n,j})$$

and with $P_n = \{\alpha_{n,1}, \alpha_{n,2}, ..., \alpha_{n,m}\}$ we shall denote the set of zeros of this polynomial.

If $\Delta_{n,m}(f) = 0$ for $n \geq n_0$, for any power series (1) and any sequence of positive numbers $\varepsilon = \{\varepsilon\}_{n=0}^{+\infty}$ exist a power series

$$g = g(z) = \sum_{n=0}^{+\infty} g_n z^n,\ g \in \cup_\epsilon(f),$$

such that for any nonnegative integer m and n , where

$$\cup_\epsilon(f) = \{\ g : |g_n - f_n| < \epsilon_n,\ \epsilon_n : \overline{\lim_{n\to+\infty}} |\epsilon_n|^{\frac{1}{n}} = q,\ n = 0, 1, 2...\ \}\ (\ 0 \leq q < 1\ )$$

(see [6]). In such case f is replased and g is under consideration. So in further consideration if $R_m < \infty$ we consider that the following inequality is valid

$$(5) \qquad |\Delta_{n,m}(f)|\ \geq\ q_0^n\ (q \geq q_0 > 0),\ n \geq n_0,\ m = 0, 1, 2, ...$$

It is well known that the radius of m-meromorphy of the power series (1) $R_m = R_m(f)$ is given by Hadamard s formula

$$R_m(f) = \frac{\ell_m(f)}{\ell_{m+1}(f)}$$

where $\ell_0(f) = 1,\ \ell_m(f) = \overline{\lim_{n\to+\infty}} \mid \Delta_{n,m}(f) \mid^{\frac{1}{n}}$ (see [4]).

We will prove the following proposition:

Theorem. *If the following is satisfied*

$$\lim_{n\to+\infty} q_{n,m}(\alpha_i) = 0,\ \alpha_i \in C\backslash\{0\} \tag{6}$$

then

$$0 < R_0 \leq |\alpha_i| \leq R_m. \tag{7}$$

Before roving this proposition let us note that if $q_{n,m}(\alpha)$ is defined by the sequence of the coefficients of the series (1) by means of the equation (3). Then there is a polynomial $p_{n,m}(\alpha) = p_{n,m}(\alpha, f)$ such that the equality is valid

$$(q_{n,m}.f - p_{n,m})(\alpha) = A_{n,m}\alpha^{n+m+1} + ...$$

If the sequence $\{\pi_{n,m}\},\ m \in N,\ n = 1, 2, 3, ...,$

$$\pi_{n,m}(\alpha) = \pi_{n,m}(\alpha, f) = \frac{p_{n,m}(\alpha, f)}{q_{n,m}(\alpha, f)}$$

is convergent in the point $\alpha_0 \neq 0$, then $R_0 > 0$.

Remark 1. The function $\pi_{n,m}(\alpha) = \frac{p_{n,m}(\alpha)}{q_{n,m}(\alpha)}$ is called Padé approximation of the type (n, m) for the series (1) (see [1]).

Remark 2. The above statement is due to A. Gonchar and was proved in 1981 (see [3]).

Proof of the Theorem. We shall divede the proof of the Theorem in three cases.

Case 1. We shall prove that if (6) is valid than $R_0 > 0$.

Let us presume that $R_0 = 0$ .Then

$$\ell_m(f) = \overline{\lim_{n\to+\infty}} |\Delta_{n,m}(f)|^{\frac{1}{n}} = +\infty \quad or \quad \underline{\lim_{n\to+\infty}} |\Delta_{n,m-1}(f)|^{\frac{1}{n}} = 0\ .$$

But $\underline{\lim}_{n\to+\infty} |\Delta_{n,m-1}(f)|^{\frac{1}{n}} = 0$ e impossible to be valid, because (5) is valid and hence $\ell_m(f) = +\infty$.

Then $|\alpha_i| > 0$ and exists ρ $(0 < \rho < +\infty)$ such that $0 < \rho < |\alpha_i|$ and hence

$$\overline{\lim}_{n\to+\infty} |\rho^{nm}\Delta_{n,m}(f)|^{\frac{1}{n}} = \overline{\lim}_{n\to+\infty} |\rho^{nm}\Delta_{n,m}((z-\alpha)f)|^{\frac{1}{n}} > 1,$$

here α is a unspecified point of C. From where it follows that $\Lambda = \Lambda(\rho) \subset N$ exists, such that if $n \in \Lambda$ the following inequality is valid

$$\rho^{nm}|\Delta_{n,m}((z-\alpha)f)| \geq \rho^{km}|\Delta_{k,m}((z-\alpha)f)|,\ k = 1, 2, ..., n. \tag{8}$$

We denote φ the series

$$\varphi = \varphi(z) = \sum_{n=0}^{+\infty} \varphi_n z^n = \sum_{n=0}^{+\infty} f_n \alpha_i^n z^n$$

and we form the difference

$$\begin{aligned} \triangle_{n,m}(\varphi) - \triangle_{0,m}(\varphi) &= \sum_{k=1}^{n} (\triangle_{n,m}(\varphi) - \triangle_{0,m}(\varphi)) \\ &= \alpha_i^{nm} \triangle_{n,m}((z-\alpha)f).T_{n,m}\ , \end{aligned}$$

where

$$T_{n,m} = \sum_{k=1}^{n} \left\{ \frac{\frac{\rho^{km}\triangle_{k,m}((z-\alpha)f).\rho^{nm}}{\rho^{nm}\triangle_{n,m}((z-\alpha)f).\alpha_i^{nm}}}{\frac{\rho^{km}\triangle_{k,m}((z-\alpha)f)}{\triangle_{k,m}(\varphi)}} - \frac{\frac{\rho^{km}\triangle_{k,m}((z-\alpha)f).\rho^{nm}}{\rho^{nm}\triangle_{n,m}((z-\alpha)f).\alpha_i^{nm}}}{\frac{\rho^{km}\triangle_{k,m}((z-\alpha)f)}{\triangle_{k,m}(\varphi)}} \right\} .$$

From where for $n \in \Lambda,\ \alpha \in C\backslash P,\ \ P = \bigcup_{n=1}^{+\infty} P_n$ considering the inequality (8) ve have

$$|\triangle_{n,m}(\varphi) - \triangle_{0,m}(\varphi)| \leq \frac{|\alpha_i|^{nm}}{|\alpha_i|^m}\ |\triangle_{n,m}((z-\alpha)f)|\ .T^*_{n,m}\ , \tag{9}$$

where

$$T^*_{n,m} = \sum_{k=1}^{n} \left[\frac{\left(\frac{\rho}{|\alpha_i|}\right)^{(n-k)m}}{\left|q_{k,m}\left(\frac{\alpha}{\alpha_i}, \varphi\right)\right|} + \frac{\left(\frac{\rho}{|\alpha_i|}\right)^{(n-k+1)m}}{\left|q_{k-1,m}\left(\frac{\alpha}{\alpha_i}, \varphi\right)\right|} \right] .$$

We fix $n \in \Lambda$ and unspecified $\epsilon > 0$. For any k=1,2,...,n-1 we denote with $J_{k,\epsilon}$ the set consisting of ϵ/mk^2 -surroundings of the zeros of the polynomial $q_{k,m}(\alpha, f)$. We put $J_\epsilon^n = \bigcup\limits_{k=1}^{n-1} J_{k,\epsilon}$. The sum of the diameters of the disks included in the set J_ϵ^n does not exceed the quantity $\epsilon \sum\limits_{k=1}^{n-1} \frac{1}{k^2}$. Then a circumference γ_n with a centre in the point α_i and the radius r_n exists which is not cut with the set J_ϵ^n. Then for any $\alpha \in \gamma_n$ and $k = 1, 2, ..., n$ we have

$$|q_{k,m}(\alpha, f)| \geq c_1 \left(\frac{\epsilon}{mk^2}\right)^m = c_2 k^{-2m} \ , \tag{10}$$

wher the quantities $c_1 > 0$ and $c_2 > 0$ don t depend on k (and on n).

Then from (9) using (10) we have

$$|\triangle_{n,m}(\varphi) - \triangle_{0,m}(\varphi)| \leq$$

$$\leq c_3 . \left| \triangle_{n,m} \left((z - \frac{\alpha}{\alpha_i}) \varphi \right) \right| . \sum_{k=1}^{m} k^{2m} \left(\frac{\rho}{|\alpha_i|} \right)^{(n-k)m} \leq$$

$$\leq c_3 . |\triangle_{n,m} \left((z - \frac{\alpha}{\alpha_i}) \varphi \right) | . \sum_{k=1}^{m} k^{2m} \left(\frac{\rho}{|\alpha_i|} \right)^{km} \leq$$

$$\leq c_3 . \left| \triangle_{n,m} \left((z - \frac{\alpha}{\alpha_i}) \varphi \right) \right| . \sum_{k=1}^{+\infty} k^{2m} \left(\frac{\rho}{|\alpha_i|} \right)^{km} \leq$$

$$\leq c_4 . \left| \triangle_{n,m} \left((z - \frac{\alpha}{\alpha_i}) \varphi \right) \right| , \ \alpha \in \gamma_n \ , \ n \in \Lambda \ .$$

Hence $|\triangle_{n,m}(\varphi)| \leq c_5 . \left| \triangle_{n,m} \left((z - \frac{\alpha}{\alpha_i}) \varphi \right) \right| , \ \alpha \in \gamma_n \ , \ n \in \Lambda$.

From the last inequality applying the maximum principle and using considering that

$$\left| \triangle_{n,m} \left((z - \frac{\alpha}{\alpha_i}) \varphi \right) \right| \Rightarrow +\infty \ , \ n \to +\infty \ , \ \alpha \in \bigcup (\alpha_i, r_n)$$

we have

$$\left| \frac{\triangle_{n,m}(\varphi)}{\triangle_{n,m} \left((z - \frac{\alpha}{\alpha_i}) \varphi \right)} \right| \leq c_6 \ , \ \ \alpha \in \bigcup (\alpha_i, r_n) \ , \ n \in \Lambda \ .$$

i.e.

$$\left| q_{n,m}\left(\frac{\alpha}{\alpha_i},\varphi\right)\right|^{-1} \le c_6\ ,\quad \alpha \in \bigcup(\alpha_i, r_n)\ ,\ n \in \Lambda\ .$$

But this is contrary to the condition (6), since the condition (6) satisfies then and only then, when

$$\lim_{n\to+\infty} q_{n,m}\left(\frac{\alpha}{\alpha_i},\varphi\right) = 0$$

when $\alpha = \alpha_i$.

The obtained contradiction prove that $R_0 > 0$.

Case 2. We shall prove that if the condition (6) is valid then $|\alpha_i| \ge R_0$.

From 1 it follows that $R_0 > 0$ and hence $R_0 \le \ell_m^{\frac{-1}{m}}(f) \le R_m$.

Let us presume that $|\alpha_i| < R_0$. Then ρ_1 ($0 < \rho_1 < +\infty$) exists such that we have

$$|\alpha_i| < \rho_1 < R_0 \le \ell_m^{\frac{-1}{m}}(f) \tag{11}$$

and hence for every $\alpha \in C, \alpha$ is different from the poles of f in D_m we obtain

$$\overline{\lim_{n\to+\infty}} |\rho_1^{nm}\Delta_{n,m}(f)|^{\frac{1}{n}} = \overline{\lim_{n\to+\infty}} |\rho_1^{nm}\Delta_{n,m}((z-\alpha)f)|^{\frac{1}{n}} < 1,$$

Then

$$\lim_{n\to+\infty} \rho_1^{nm}|\Delta_{n,m}((z-\alpha)f)| = 0$$

and $\Lambda_1 = \Lambda_1(\rho) \subset N$ exists such that when $n \in \Lambda_1$ the following inequality is valid

$$\rho_1^{nm}|\Delta_{n,m}((z-\alpha)f)| \ge \rho_1^{(n+j)m}|\Delta_{n+j,m}((z-\alpha)f)|, j = 0,1,2,...,\ . \tag{12}$$

In that case using (11) vhen $n \in \Lambda_1$ the following

$$\left|\frac{\triangle_{n+j,m}(f)}{\triangle_{n,m}(f)}\right| \le \frac{1}{\rho_1^{jm}} < \frac{1}{|\alpha_i|^{jm}}, j = 1,2,... \tag{13}$$

is valid also.

We denote φ the series

$$\varphi = \varphi(z) = \sum_{n=0}^{+\infty} \varphi_n z^n = \sum_{n=0}^{+\infty} f_n\alpha_i^n z^n$$

and we form the difference

$$\triangle_{n+k,m}(\varphi)-\triangle_{n,m}(\varphi)=\sum_{j=1}^{k}(\triangle_{n+j,m}(\varphi)-\triangle_{n+j-1,m}(\varphi))$$
$$=\alpha_i^{nm}\triangle_{n,m}((z-\alpha)f).T_{k,m}\ ,$$

where

$$T_{k,m}=\sum_{j=1}^{k}\left\{\frac{\frac{\rho_1^{(n+j)m}\triangle_{n+j,m}((z-\alpha)f).\rho_1^{nm}}{\rho_1^{nm}\triangle_{n,m}((z-\alpha)f).\alpha_i^{nm}}}{\frac{\rho_1^{(n+j)m}\triangle_{n+j,m}((z-\alpha)f)}{\triangle_{n+j,m}(\varphi)}}-\frac{\frac{\rho_1^{(n+j-1)m}\triangle_{n+j-1,m}((z-\alpha)f).\rho_1^{nm}}{\rho_1^{nm}\triangle_{n,m}((z-\alpha)f).\alpha_i^{nm}}}{\frac{\rho_1^{(n+j-1)m}\triangle_{n+j-1,m}((z-\alpha)f)}{\triangle_{n+j-1,m}(\varphi)}}\right\}\ .$$

From where for $n\in\Lambda,\ \alpha\in C\backslash P,\ \ P=\bigcup_{n=1}^{+\infty}P_n$ using the inequality (12) ve obtain

$$|\triangle_{n+k,m}(\varphi)-\triangle_{n,m}(\varphi)|\le\frac{|\alpha_i|^{nm}}{|\alpha_i|^m}\ |\triangle_{n,m}((z-\alpha)f)|\ .T^*_{k,m}\ , \tag{14}$$

where

$$T^*_{k,m}=\sum_{j=1}^{k}\left[\frac{\left(\frac{|\alpha_i|}{\rho_1}\right)^{jm}}{\left|q_{n+j,m}\left(\frac{\alpha}{\alpha_i},\varphi\right)\right|}+\frac{\left(\frac{|\alpha_i|}{\rho_1}\right)^{(j-1)m}}{\left|q_{n+j-1,m}\left(\frac{\alpha}{\alpha_i},\varphi\right)\right|}\right]\ .$$

We fix $n\in\Lambda_1$ and unspecified $\epsilon>0$. For any j=1,2,...,k we denote with $J_{j,\epsilon}$ the set consisting of ϵ/mj^2 -surroundings of the zeros of the polynomial $q_{n+j,m}(\alpha,f)$. We put $J_\epsilon^k=\bigcup_{j=1}^{k}J_{j,\epsilon}$. The sum of the diameters of the disks included in the set J_ϵ^k does not exceed the quantity $\epsilon\sum_{j=1}^{k}\frac{1}{j^2}$. Then a circumference γ_k with a centre in the point α_i and the radius r_k exists which is not cut with the set J_ϵ^k and for any $\alpha\in\gamma_k$ and $j=1,2,...,k$ we have

$$|q_{n+j,m}(\alpha,f)|\ge c_1\left(\frac{\epsilon}{mj^2}\right)^m=c_2j^{-2m}\ , \tag{15}$$

wher the quantities $c_1>0$ and $c_2>0$ don t depend on j (and on n).

Then from (14) using (15) we have

$$|\triangle_{n+k,m}(\varphi) - \triangle_{n,m}(\varphi)| \leq$$

$$\leq c_2 . \left|\triangle_{n,m}\left((z - \frac{\alpha}{\alpha_i})\varphi\right)\right| . \sum_{j=1}^{k} j^{2m} \left(\frac{|\alpha_i|}{\rho_1}\right)^{(j-1)m} \left[\left(\frac{|\alpha_i|}{\rho_1}\right)^m + 1\right] \leq$$

$$\leq c_3 . \left|\triangle_{n,m}\left((z - \frac{\alpha}{\alpha_i})\varphi\right)\right| . \sum_{j=1}^{k} j^{2m} \left(\frac{|\alpha_i|}{\rho_1}\right)^{(j-1)m} \leq$$

$$\leq c_3 . \left|\triangle_{n,m}\left((z - \frac{\alpha}{\alpha_i})\varphi\right)\right| . \sum_{j=1}^{+\infty} j^{2m} \left[\left(\frac{|\alpha_i|}{\rho_1}\right)^m\right]^{(j-1)} \leq$$

$$\leq c_4 . \left|\triangle_{n,m}\left((z - \frac{\alpha}{\alpha_i})\varphi\right)\right| , \ \alpha \in \gamma_k \ , \ n \in \Lambda_1 \ .$$

From the last inequality we obtain that

$$\left|\frac{\triangle_{n+k,m}(\varphi)}{\triangle_{n,m}(\varphi)} - 1\right| \leq c_4 . \left|\frac{\triangle_{n,m}\left((z - \frac{\alpha}{\alpha_i})\varphi\right)}{\triangle_{n,m}(\varphi)} - 1\right| , \ \alpha \in \gamma_k \ , \ n \in \Lambda_1 \ .$$

From where using the maximum principle it follows that

$$\left|\frac{\triangle_{n+k,m}(\varphi)}{\triangle_{n,m}(\varphi)} - 1\right| \leq c_4 . \left|q_{n,m}\left(\frac{\alpha}{\alpha_i}, \varphi\right)\right| \ , \quad \alpha \in \bigcup(\alpha_i, r_n) \ , \ n \in \Lambda_1 \ .$$

Then from the condition (6) we obtain that for $\alpha = \alpha_i$

$$\lim_{n \to +\infty} q_{n,m}\left(\frac{\alpha}{\alpha_i}, \varphi\right) = 0$$

and therefore hence

$$\lim_{n \to +\infty} \frac{\triangle_{n+k,m}(\varphi)}{\triangle_{n,m}(\varphi)} = 1 \ , \ n \in \Lambda_1 \ , \ k = 0, 1, 2, ... \ .$$

From where it follows that

$$\lim_{n \to +\infty} \frac{\alpha_i^{(n+k)m} \triangle_{n+k,m}(f)}{\alpha_i^{nm} \triangle_{n,m}(f)} = 1 \ , \ n \in \Lambda_1 \ , \ k = 0, 1, 2, ... \ .$$

and this contradicts the inequality (13). The obtained contradiction prove that if the condition (6) is valid then $|\alpha_i| \geq R_0$.

Case 3. We shall prove that if (6) is valid then $|\alpha_i| \leq R_m$.

Let us presume that $|\alpha_i| > R_m$. Then ρ_2 ($0 < \rho_2 < +\infty$) exists such that

$$|\alpha_i| > \rho_2 > R_m \geq \ell_m^{\frac{-1}{m}}(f)$$

and hence for every $\alpha \in C, \alpha$ is different from the poles of f in D_m we have

$$\overline{\lim_{n\to+\infty}} |\rho_2^{nm}\Delta_{n,m}(f)|^{\frac{1}{n}} = \overline{\lim_{n\to+\infty}} |\rho_2^{nm}\Delta_{n,m}((z-\alpha)f)|^{\frac{1}{n}} > 1 \ .$$

Then $\Lambda_2 = \Lambda_2(\rho_2) \subset N$ exists such that for $n \in \Lambda_2$ the following inequality is valid

$$\rho_2^{nm}|\Delta_{n,m}((z-\alpha)f)| \geq \rho_2^{km}|\Delta_{k,m}((z-\alpha)f)| \ , k = 1, 2, ..., n \ .$$

We denote φ the series

$$\varphi = \sum_{n=0}^{+\infty} \varphi_n z^n = \sum_{n=0}^{+\infty} f_n \alpha_i^n z^n$$

and we form the difference

$$\triangle_{n,m}(\varphi) - \triangle_{0,m}(\varphi) = \sum_{k=1}^{n} (\triangle_{k,m}(\varphi) - \triangle_{k-1,m}(\varphi)) \ .$$

We reform this difference the same way as in 1 and through analogous to accomplished there arguments we reach to contradiction. The obtained contradiction prove that if the condition (6) is valid then $|\alpha_i| \leq R_m$. The prove of the theorem is complete. □

Analogous questions when the convergence in (6) is geometric are considered in [3] and when the convergence is unspecified in [2] and [5]. Suggested here method for solving the problem is different from that in previous works and it gives more information.

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МЕРОМОРФНА ПРОДЪЛЖИМОСТ НА СТЕПЕННИ РЕДОВЕ

Петър Янков

Резюме. В работата, посредством специално дефиниран чрез коефициентите на Тейлоров ред полином $q_{n,m}(\alpha)$, се доказва твърдение, даващо възможност да се прави преценка за мероморфна продължимост на степенни редове.